

# Mission-Level Autonomy

## Autonomous Rotorcraft Project

Michael Freed

NASA Ames Research Center

# People

## Apex Dev Team

Michael Freed

Michael Dalal

Will Fitzgerald

Dawn Fitzpatrick

Robert Harris

## Users

NASA (several groups)

FAA

MITRE

Microanalysis and Design

Smart Information Flow Technologies

Applied Physics Lab

Dynamic Research Inc.

BBN

CMU

Stanford

George Mason University

University of Maryland

RPI

# Background

## Autonomy research at NASA

- Decades of investment by wide range of programs
- Particular emphasis at Ames, Intelligent Systems Division

## Apex Project – reusable autonomy software

- Began in 1997, supported out of several programs

## Autonomous Rotorcraft Project

- Began in 2001, as part of NASA Intelligent Systems program. Rotorcraft seen as important platform for terrestrial applications (Earth Science) and as analogue for planetary exploration vehicles.
- Early objective was to develop autonomy capabilities useful to both Army and NASA

# Outline

- Apex: autonomy software overview
- Autonomous surveillance missions
- Automatically generating mission plans
- Observing targets
- Adapting to unplanned conditions
- Visualizing autonomy logic



# Outline

- Apex: autonomy software overview
- Autonomous surveillance missions
- Automatically generating mission plans
- Observing targets
- Adapting to unplanned conditions
- Visualizing autonomy logic

# Apex Project Background

## Objectives and Approach

- Objective:** Reusable for diverse missions/platforms
- **Capabilities** enhanced by use in diverse applications by dev team and external users (~200)
  - **Reduced cost/difficulty** by continuous improvement in software qualities, documentation, tools...
  - **Usability** continuously improved in response to user feedback: behavior specification, visualization tools, APIs, ...

# Apex Project Background

## Applications

**Real  
Robot**

### Autonomous Rotorcraft Project

intelligent surveillance and reconnaissance



**Simulated  
Robot**

### Mission Simulation Facility / REF

**Riptide** High-fidelity flight simulation

**AuRA** Wildfire detection, Earth Science

**X-Plane** Flight failure detection/recovery

**Real  
Human**

### Astronaut Procedure Guidance

**CPM-GOMS** HCI Analysis

**VAMS** Virtual Participants in HIL Simulations

**MIDAS** HCI Analysis

**Dynamic Research Inc.** Accident Analysis

**Simulated  
Human**



# Apex Project Background

## System Overview

### System elements

- Agent architecture, reasoning and control services, behavior representation language (PDL)
- Sherpa (autonomy logic and behavior visualization)
- Simulation engine (prototyping support)
- APIs, interop support (HLA, DOMS, UDP, TCP, XML)
- Support for install, update, portability
- Manual, sample apps, web site
- Publications

# Three Layer Architecture

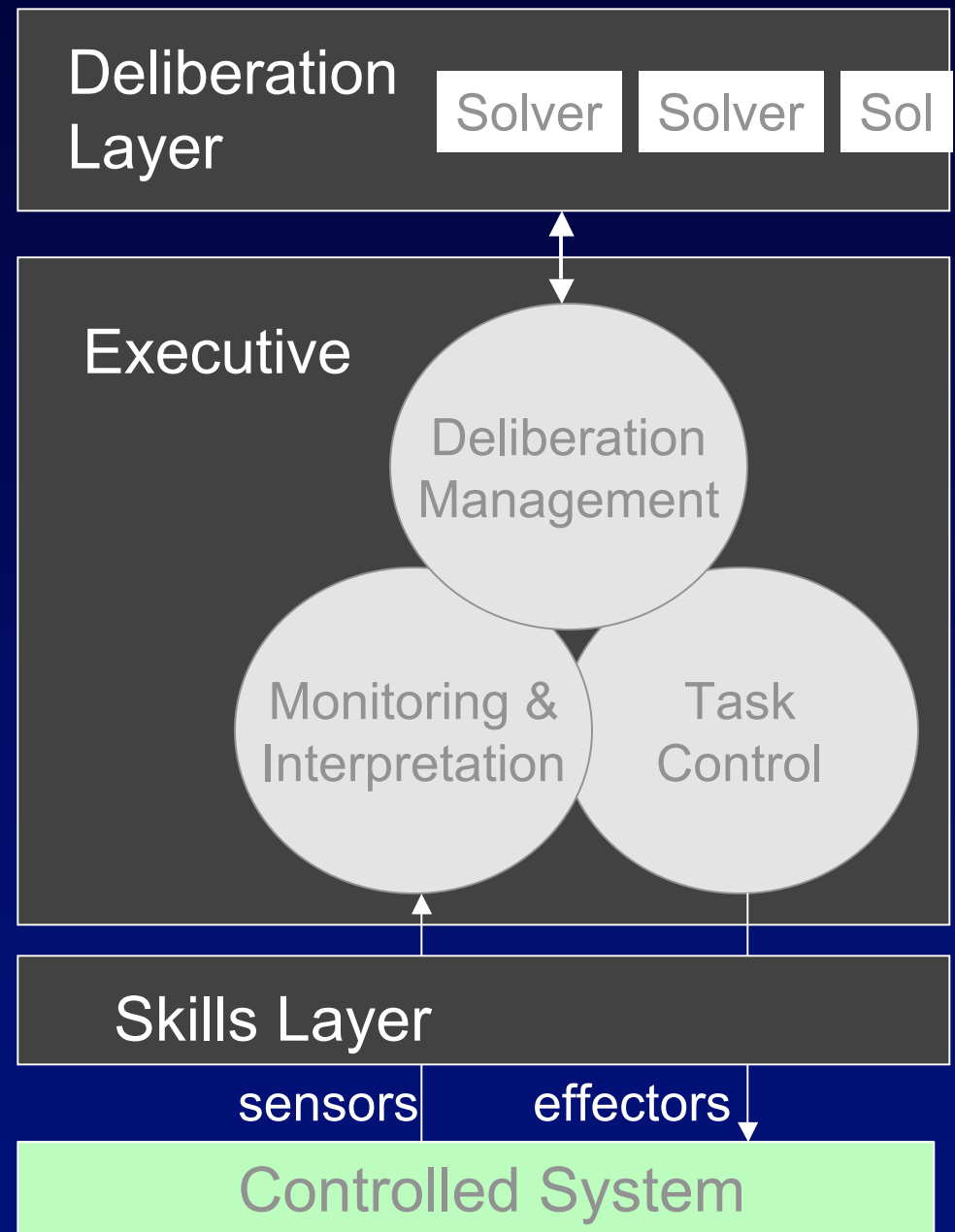
**Top:** slow/costly *solver* alg's  
e.g. AI planner, path planner

**Mid:** responsive reasoning &  
control functions

**Bottom:** sensor processing &  
effector control

## Principal design concepts

1. Separation of fast/slow
2. Separation of reusable from application-specific



# Autonomy Architecture

E.g. Autonomous Rotorcraft Project

## Deliberation Layer

Periodic surveillance planning

## Goal Executive Layer

Basic plan execution

Tactical observation maneuvers

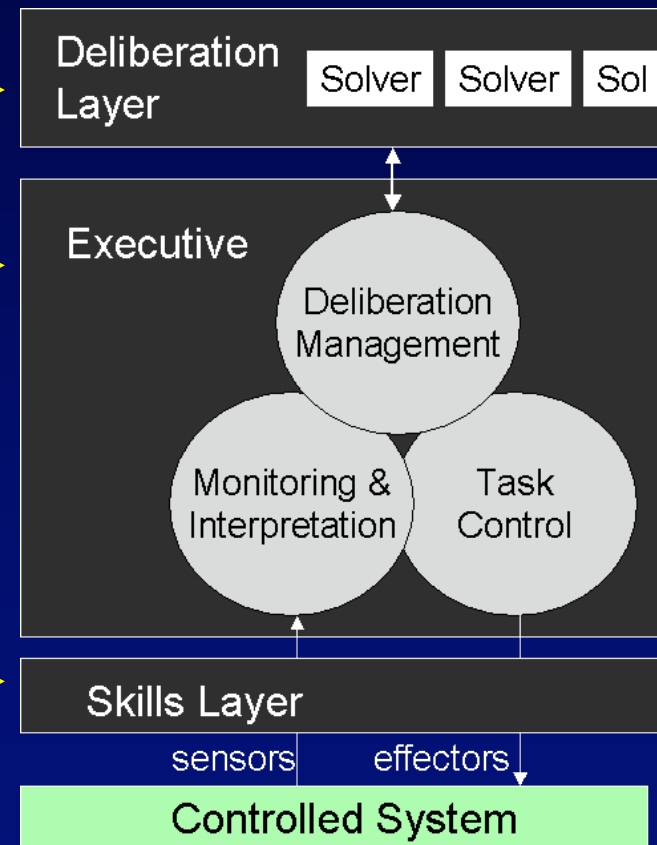
Monitoring and anomaly-handling

Human interaction management

## Skills (application-specific)

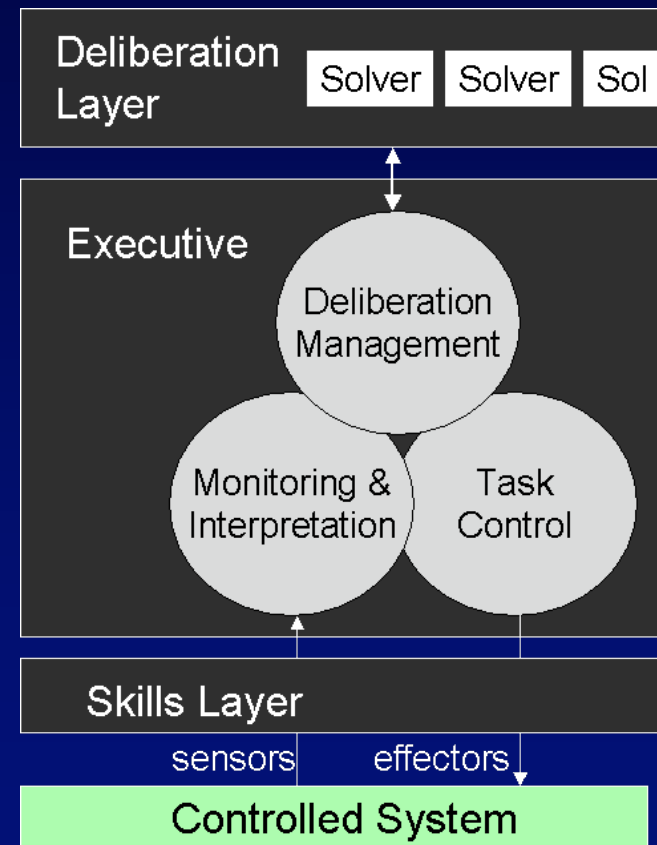
Autopilot

Payload controllers



# Reasoning and Control Services

Dispatch  
Signal and process handling  
Condition detection  
Memory management  
Refinement  
Transformation  
Projection  
Self-calibration  
Deliberation control



# Outline

- Apex: autonomy software overview
- **Autonomous surveillance missions**
- Automatically generating mission plans
- Observing targets
- Adapting to unplanned conditions
- Visualizing autonomy logic

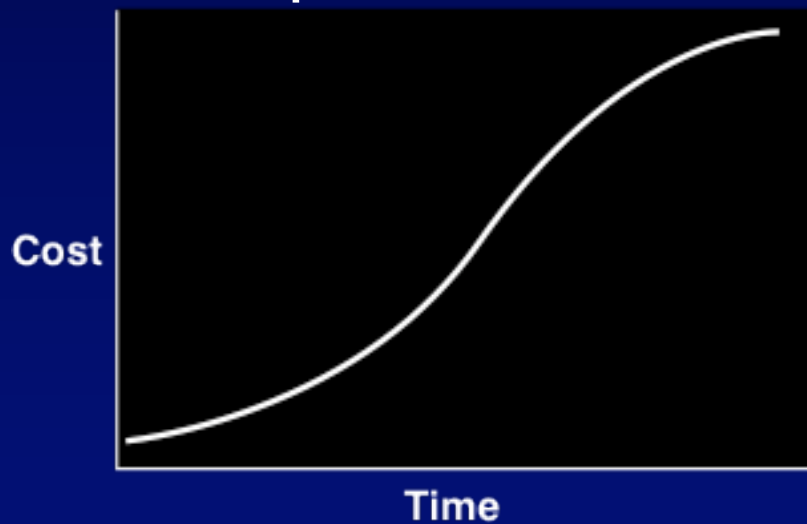


# Mission-level Autonomy Focus

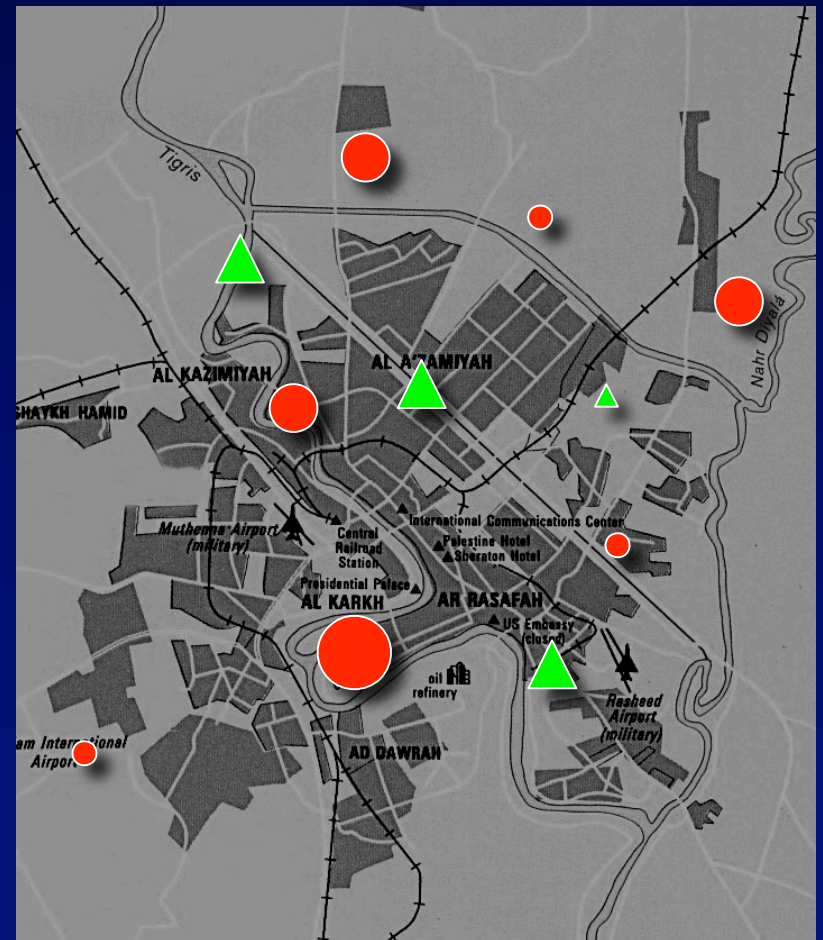
## Periodic Surveillance

- **Given:** many targets to monitor with one/few aircraft
- **Objective:** early change awareness
- **Decide:** where to go next

Example: fire detection



Observe frequently to minimize fire detection latency

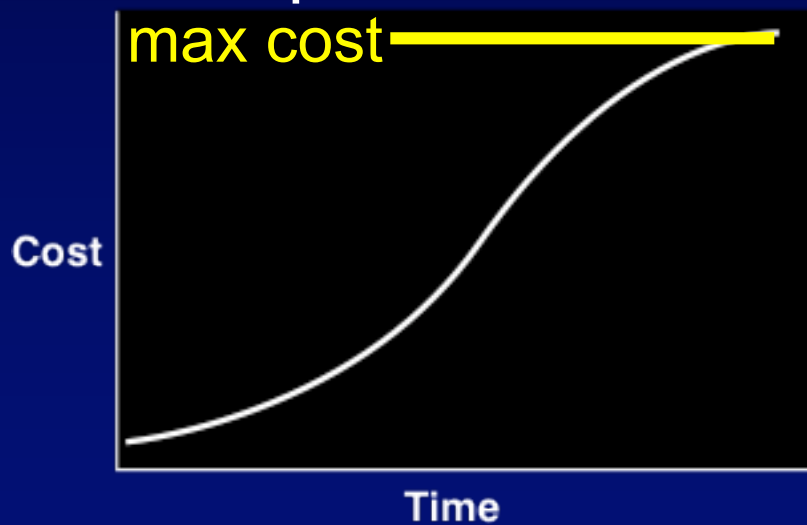


# Mission-level Autonomy Focus

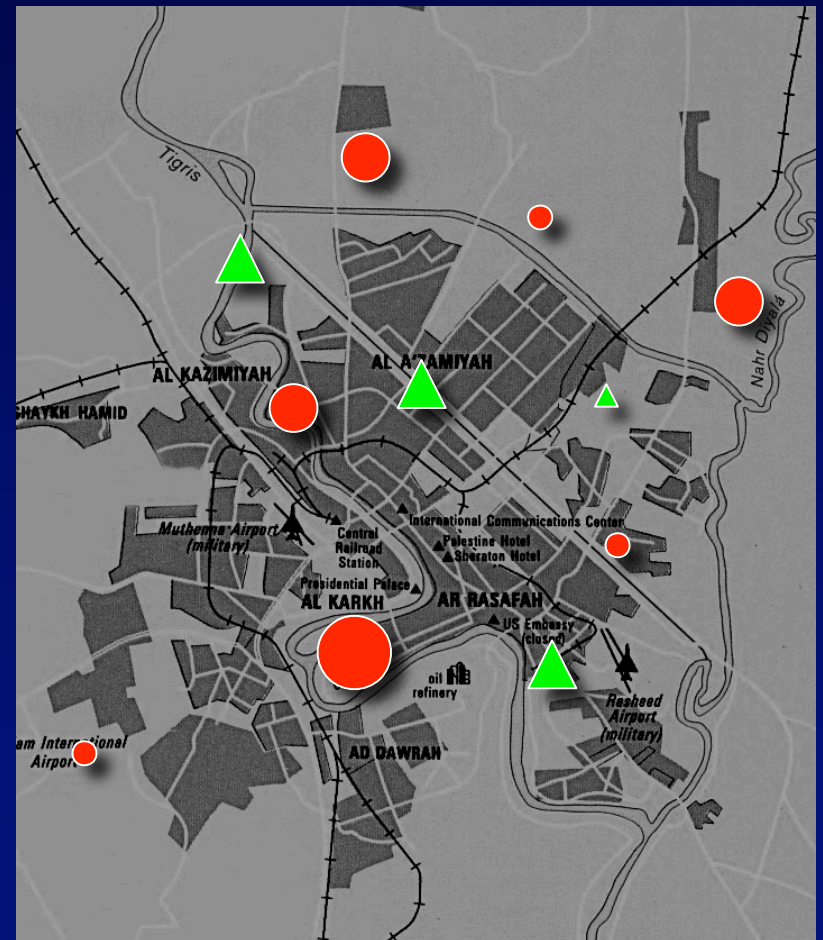
## Periodic Surveillance

- **Given:** many targets to monitor with one/few aircraft
- **Objective:** early change awareness
- **Decide:** where to go next

Example: fire detection



Possibly visit more valuable targets more often

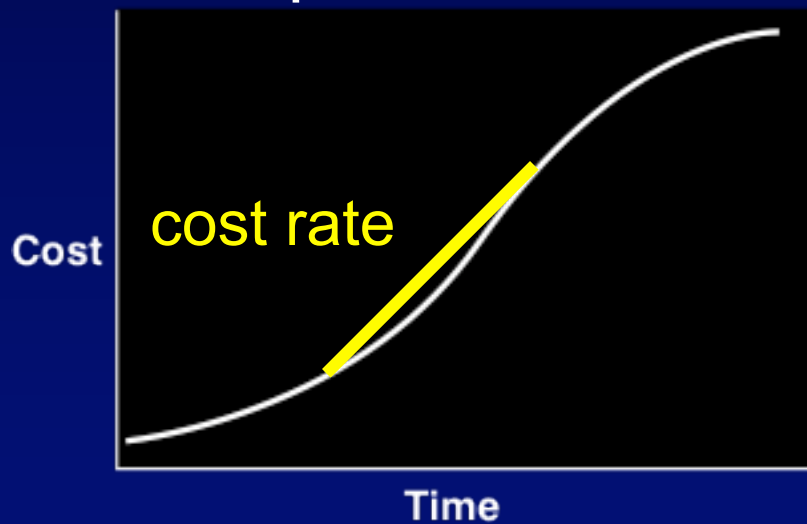


# Mission-level Autonomy Focus

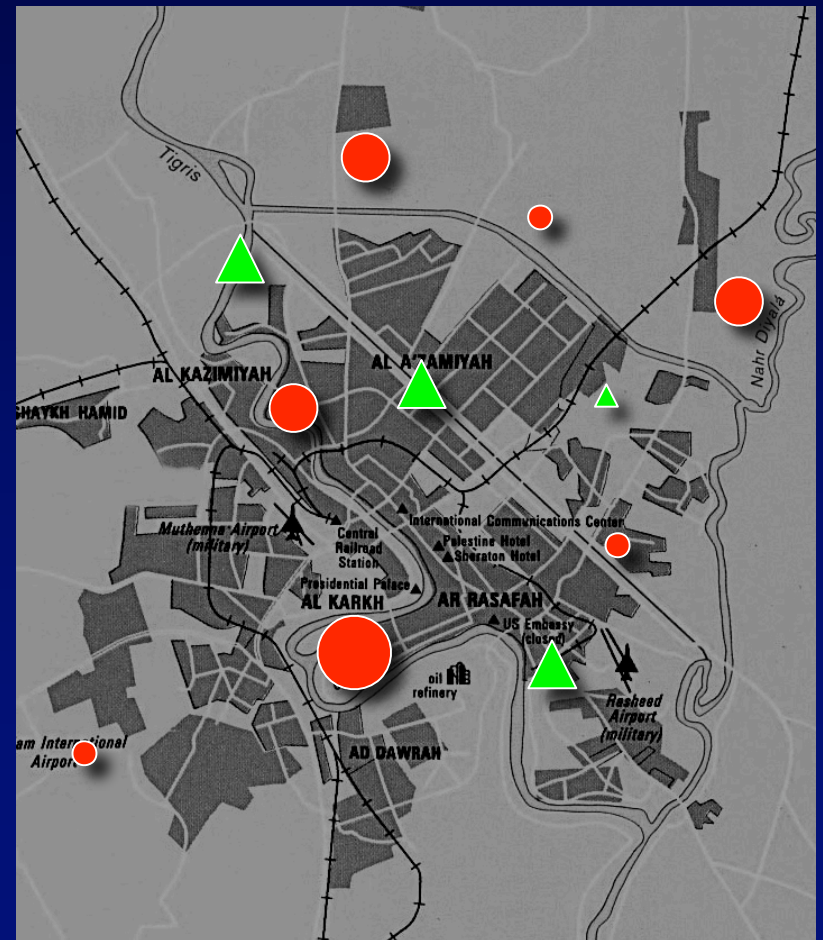
## Periodic Surveillance

- **Given:** many targets to monitor with one/few aircraft
- **Objective:** early change awareness
- **Decide:** where to go next

Example: fire detection



Visit least stable “neediest”  
targets more often or never



# Surveillance task performance

## A decision-theoretic approach

$$ECI = \sum_T^{\text{Targets}} \sum_1^{\text{Intervals}} \int_{t=t_1}^{t_2} p(t) \cdot \text{Cost}(t_2 - t) dt$$

**ECI:** expected cost of ignorance

**Targets:** locations to be monitored for some event

**Intervals:** period between successive observations

**p(t):** probability density function for event

**Cost(t):** expected cost if event occurs at time t

Goal of surveillance planning is to minimize ECI

# Measuring Surveillance Performance

## Fire example

Probability of occurrence (pdf)

$$p(t) = ae^{-at} \quad \leftarrow \text{exponential}$$

Cost of occurrence  $\swarrow$  sigmoid

$$\text{cost}(d) = c_0 + \left( \frac{2}{1 + e^{-k(d+l_1+l_2)}} - 1 \right) (m - c_0)$$

Expected cost of ignorance  $[t_1 \ t_2]$

$$\text{ECI}_{\tau}(t_1, t_2, a, k, m) = \int_{t=t_1}^{t_2} ae^{-at} m \left( \frac{2}{1 + e^{-k(t_2-t)}} - 1 \right) dt$$

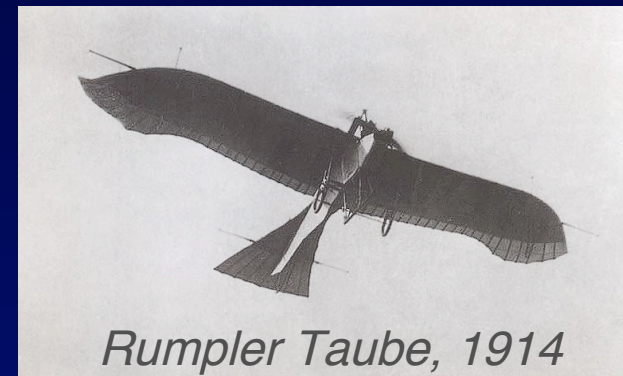




# Mission-level Autonomy Focus

## Periodic Surveillance

- State of practice:  
Remotely piloted UAVs
- Why autonomy?
  - **Fatigue**: long/uneventful tasks hard on human operators
  - **Effectiveness**: people poor at complex optimization problems
  - **Integration**: autonomy + better, cheaper UAVs can function as part of unsupervised sensor net



# Autonomous Surveillance

Objective: fully autonomous optimal surveillance

1. Generating mission plans
2. Executing mission plans in dynamic, uncertain conditions

# Outline

- Apex: autonomy software overview
- Autonomous surveillance missions
- Automatically generating mission plans
- Observing targets
- Adapting to unplanned conditions
- Next steps



# Specifying mission goals

**Mission Planning Interface**

**Target values**

Name:   Incident? ☐

[Help](#)

Value:  Cost Δ:  % Prob.  year

Maneuver:  collect:

Ht:  Easting/Northing:

**Targets**

**Mission Parameters**

Map:  Stored targets:

Select target set...

Map icons:  Max mission length:  min.

**Mission Actions**

**Apex**

**AUTONOMOUS ROTORCRAFT PROJECT**

# Autonomy Architecture

E.g. Autonomous Rotorcraft Project

## Deliberation Layer

Periodic surveillance planning

## Goal Executive Layer

Basic plan execution

Tactical observation maneuvers

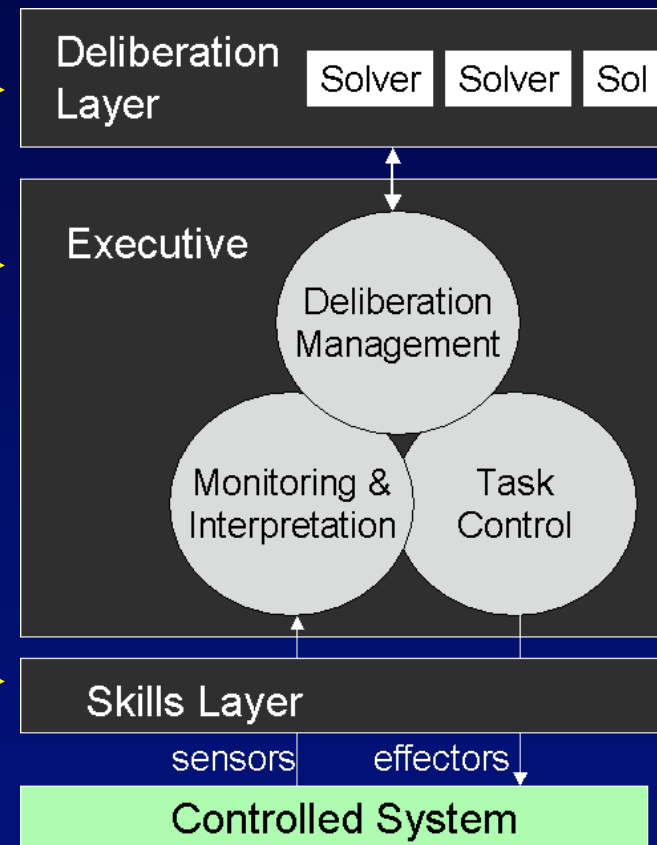
Monitoring and anomaly-handling

Human interaction management

## Skills (application-specific)

Autopilot

Payload controllers



# Mission Planning challenges

1. Creating effective surveillance planning algorithm(s)
2. Determining at runtime which planning algorithm to use
3. Metrics: how well are we doing compared to state of practice (human-directed surveillance)?

# Surveillance Planning Algorithms

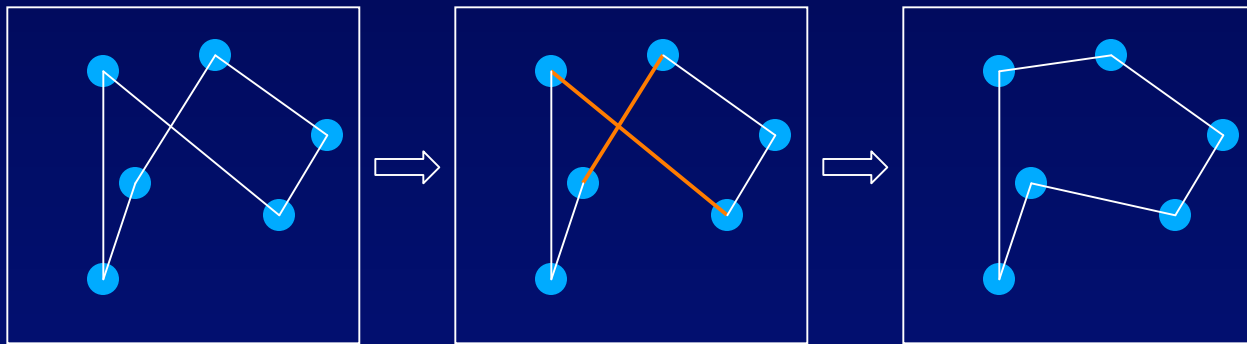
- Traveling Salesman Problem (TSP)
- Orienteering Problem
  - Time maximum (visit only subset of targets)
  - Reward varies for individual targets
- Surveillance Problem
  - Repeat visits yield multiple rewards
  - Reward value time-varying
  - Traverse time-cost state-dependent

# Planning Approach #1

## Best Cycle (local search)

### Modified 2-OPT Exchange algorithm

- Basic 2-OPT computes approximate solutions for TSP
- Approach: start with a random tour; iteratively find and apply a tour-improving exchange of 2 tour segments until none found

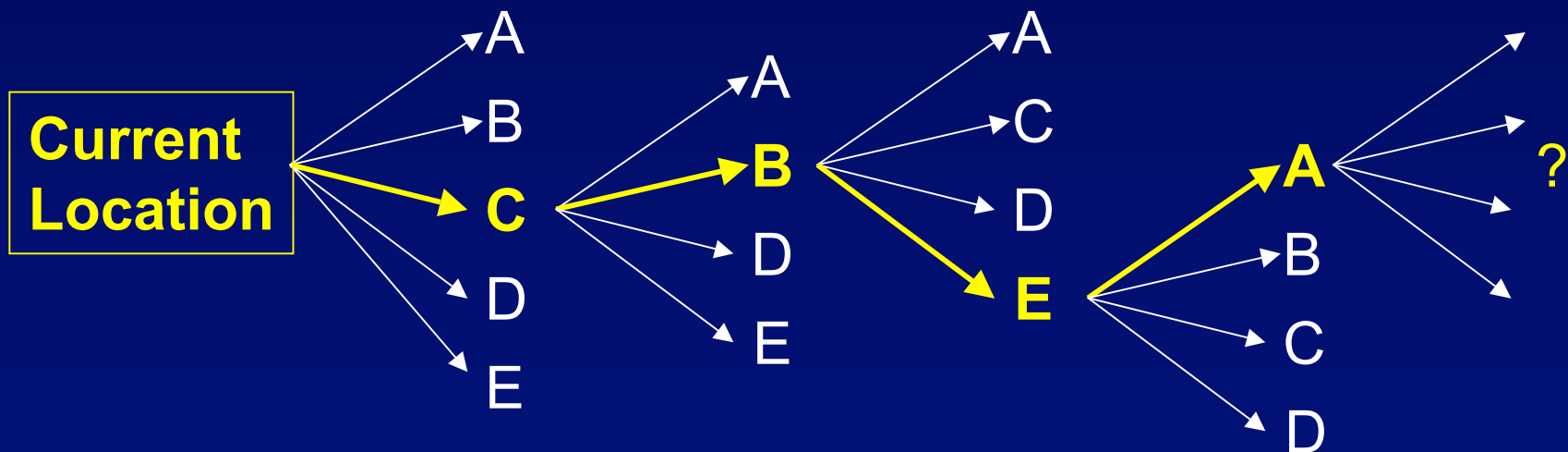


- **Modifications**
  - Use UAV kinematics model (“smoother”) to compute traverse time
  - Evaluate return-to-home point given maximum flight duration = 60 minutes

# Planning Approach #2

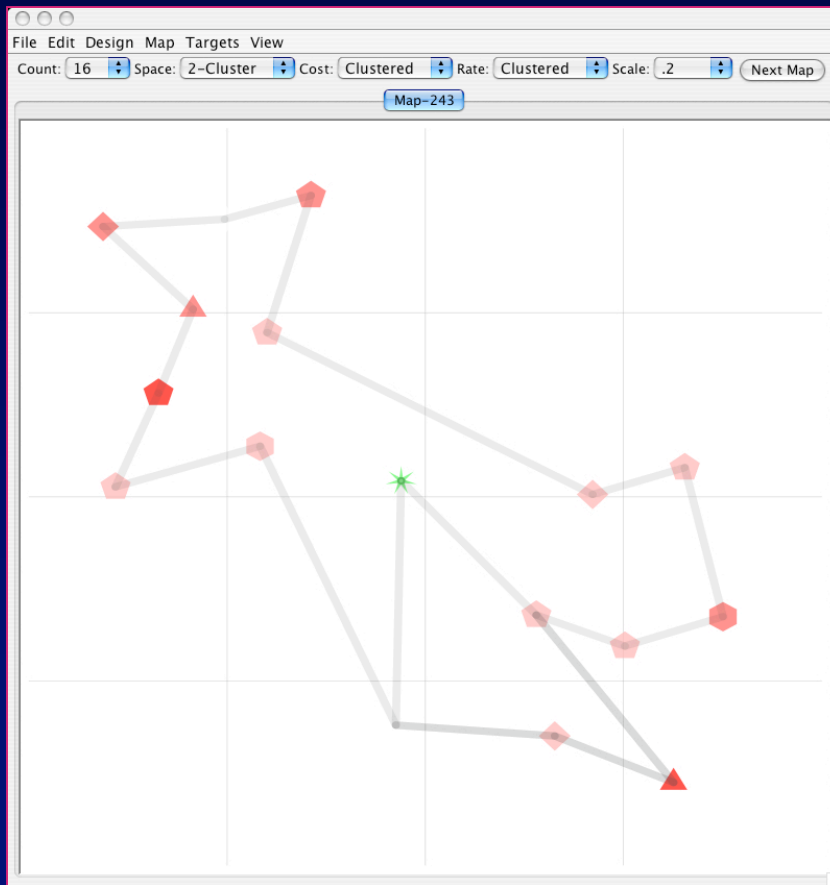
## Best Path (heuristic depth-first search)

- Best-first (WAM), beam-search (IMMP)
- Heuristic transit time (accurate), visit-recency, cost-max



# Planning Approach #3

## Human as planner (state of practice)



UI for human subjects in surveillance performance experiment

## Experiment Design

### 243 Conditions, 5 IVs

1. Number of targets
2. Spatial Distribution
3. Spatial Scale
4. Maxcost Distribution
5. Cost-Rate Distribution

- 7 subjects
- One trial per condition
- Randomly ordered
- Given training, practice and scoring decision aid
- ~6 hours / subject



# Picking the Best Surveillance Planner

Min of Best			Count Space								
Scale	Rate	Cost	4			8			16		
			2-Cluster	Globular	Uniform	2-Cluster	Globular	Uniform	2-Cluster	Globular	Uniform
Large	Clustered	Clustered	1	1	0	3	3	1	1	3	1
		Fixed	1	1	0	3	3	1	2	3	2
		Uniform	1	2	1	1	2	1	1	1	1
	Fixed	Clustered	1	1	0	1	1	1	1	3	1
		Fixed	1	1	0	3	1	1	2	3	2
		Uniform	1	1	1	1	2	1	1	3	1
	Uniform	Clustered	1	1	2	1	3	1	1	3	1
		Fixed	1	1	2	3	3	1	2	3	1
		Uniform	1	1	1	1	2	1	1	3	1
Medium	Clustered	Clustered	2	2	0	1	2	2	2	2	2
		Fixed	1	2	0	2	2	0	2	2	2
		Uniform	1	2	2	2	2	2	2	2	2
	Fixed	Clustered	1	2	0	2	2	0	2	2	2
		Fixed	1	2	0	2	2	0	2	2	2
		Uniform	1	2	2	2	2	2	2	2	2
	Uniform	Clustered	1	2	1	2	2	2	2	2	2
		Fixed	1	2	2	2	2	2	2	2	2
		Uniform	1	2	0	2	2	2	2	2	2
Small	Clustered	Clustered	2	1	0	2	0	0	2	2	2
		Fixed	2	1	0	2	1	0	2	2	2
		Uniform	2	2	3	2	2	2	2	2	2
	Fixed	Clustered	2	1	0	1	2	2	2	2	2
		Fixed	2	1	0	2	2	2	2	2	2
		Uniform	2	1	0	2	1	0	2	2	2
	Uniform	Clustered	2	2	0	1	2	2	2	2	2
		Fixed	2	2	0	1	2	2	2	2	2
		Uniform	1	1	0	2	2	2	2	2	2

Human

2-Opt

WAM

no diff

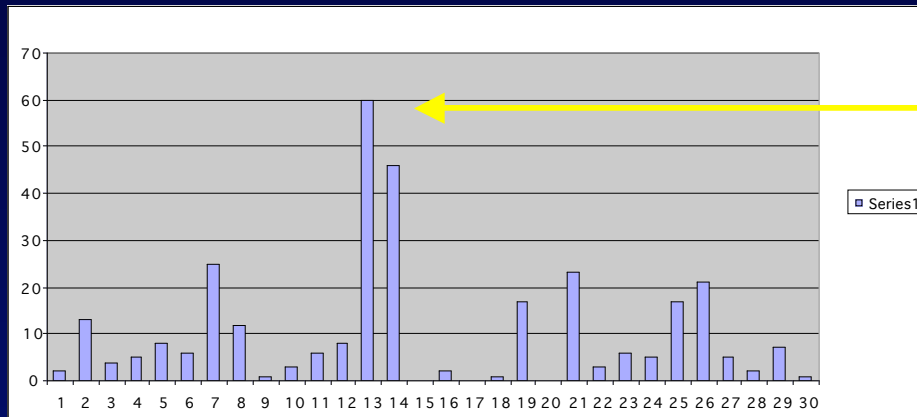


# Human Performance

- Algorithms significantly out-performed humans overall (4.9% vs. 2-Opt;  $p < 0.01$ )
- Human subjects differed significantly ( $p < 0.05$ )
- Humans did especially poorly with small-scale maps, small N, low spatial structure (uniform distribution)
- Human subjects made large errors in a small percentage of cases

*Results reinforce value of autonomous surveillance planning*

# Magnitude of differences in algorithm performance



% difference between WAM, 2-OPT

Max Performance  
Difference = 60%  
2-Opt: small, 5, perimeter

Min Performance  
Difference = 0%

## 30 conditions, 100 trials per condition

1. Number of targets: 5, 10, 20
2. Geometry: uniform, globular, perimeter, 2-cluster, 3-cluster
3. Mission space: small, large

# Automatic algorithm selection

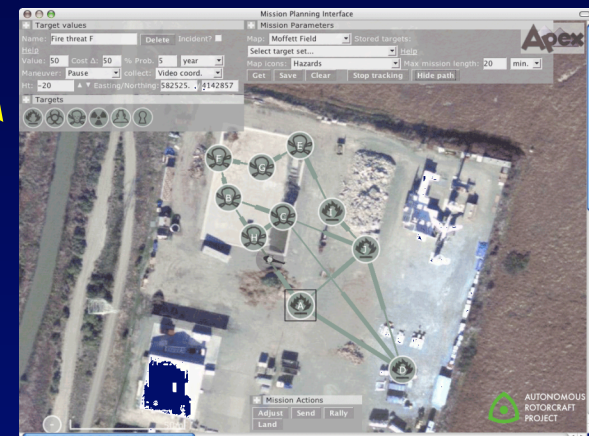
## Goal: select best algorithm given MPI-defined mission

## Method:

- Define standard mission classes
- Pre-compute performance of all available algorithms for all mission

## types; create preference table

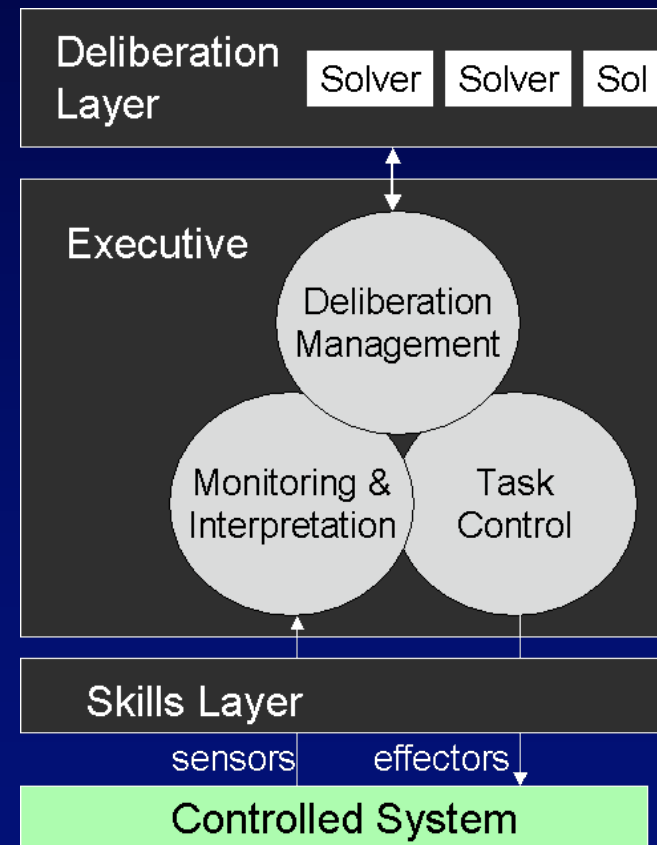
3. Rapidly classify current mission at runtime (rapidly)
4. Index into preference table



Plan of Best		Count Space									
		4			8			16			
Scale	Rate	Cost	2-Cluster	Globalbar	Uniform	2-Cluster	Globalbar	Uniform	2-Cluster	Globalbar	Uniform
Large	Clustered	Cost	1	1	0	1	1	0	1	1	0
		Fixed	1	1	0	1	1	0	1	1	0
		Uniform	1	2	0	1	2	0	1	1	1
	Fixed	Clustered	1	1	0	1	1	1	1	1	1
		Fixed	1	1	0	1	1	1	1	2	2
		Uniform	1	1	1	1	2	1	1	1	1
	Uniform	Clustered	1	1	1	2	1	2	1	1	1
		Fixed	1	1	2	1	2	1	1	2	2
		Uniform	1	1	1	1	1	1	1	2	2
Medium	Clustered	Cost	2	2	0	1	2	2	2	2	1
		Fixed	1	2	0	2	2	0	2	2	2
		Uniform	2	2	2	2	2	2	2	2	2
	Fixed	Clustered	1	2	0	2	2	0	2	2	2
		Fixed	1	2	0	2	2	0	2	2	2
		Uniform	1	2	2	2	2	2	2	2	2
	Uniform	Clustered	1	2	1	2	2	2	2	2	2
		Fixed	1	2	2	2	2	2	2	2	2
		Uniform	1	2	0	2	2	2	2	2	2
Small	Clustered	Cost	2	1	0	2	2	0	0	2	2
		Fixed	2	1	0	2	1	0	0	2	2
		Uniform	2	2	2	2	2	2	2	2	2
	Fixed	Clustered	2	1	0	1	2	2	2	2	2
		Fixed	2	1	0	2	3	3	3	3	3
		Uniform	2	1	0	2	1	0	2	2	2
	Uniform	Clustered	2	2	2	1	2	2	2	2	2
		Fixed	2	2	2	0	1	2	2	2	2
		Uniform	1	1	0	2	2	2	2	2	2

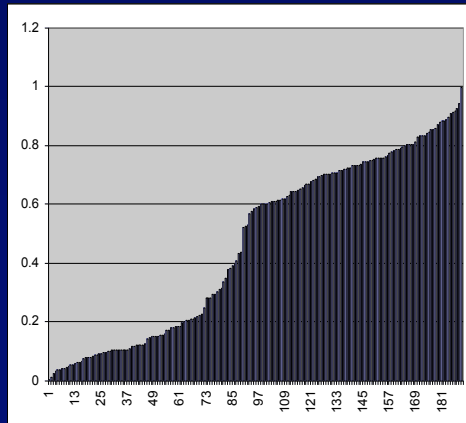
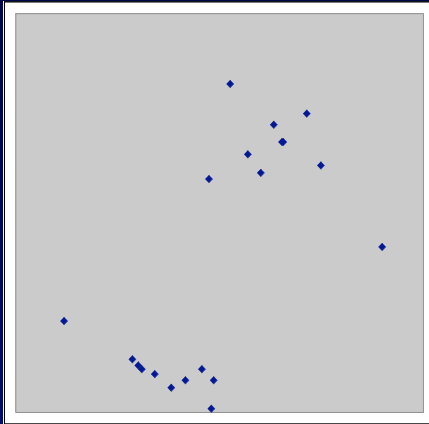
# Reasoning and Control Services

Dispatch  
Signal and process handling  
Condition detection  
Memory management  
Refinement  
Transformation  
Projection  
Self-calibration  
**Deliberation control**

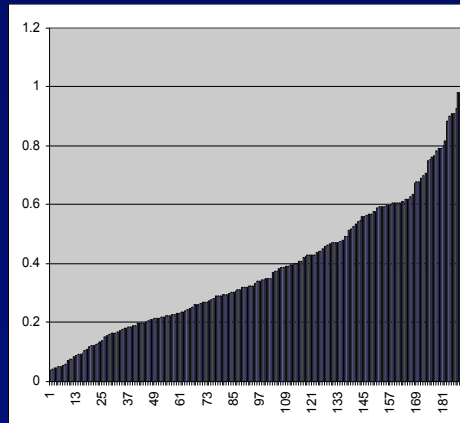
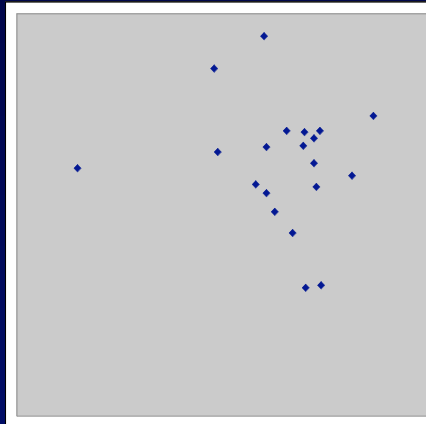


# Classifying Target Set Geometries

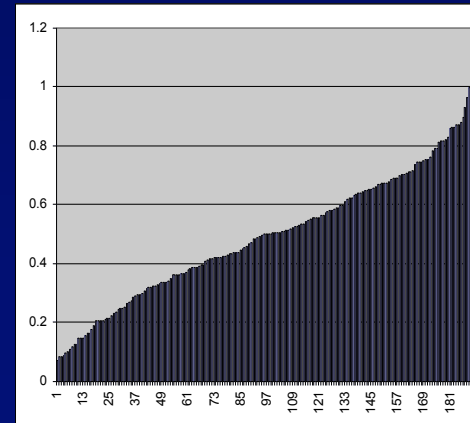
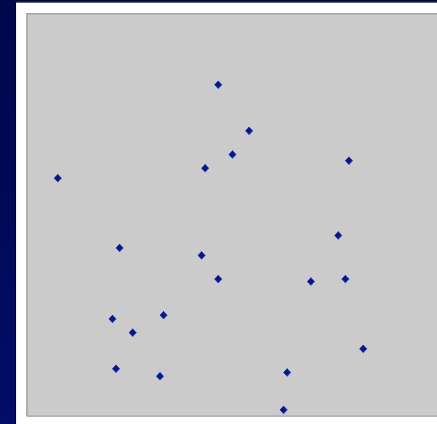
## Multicluster



## Globular

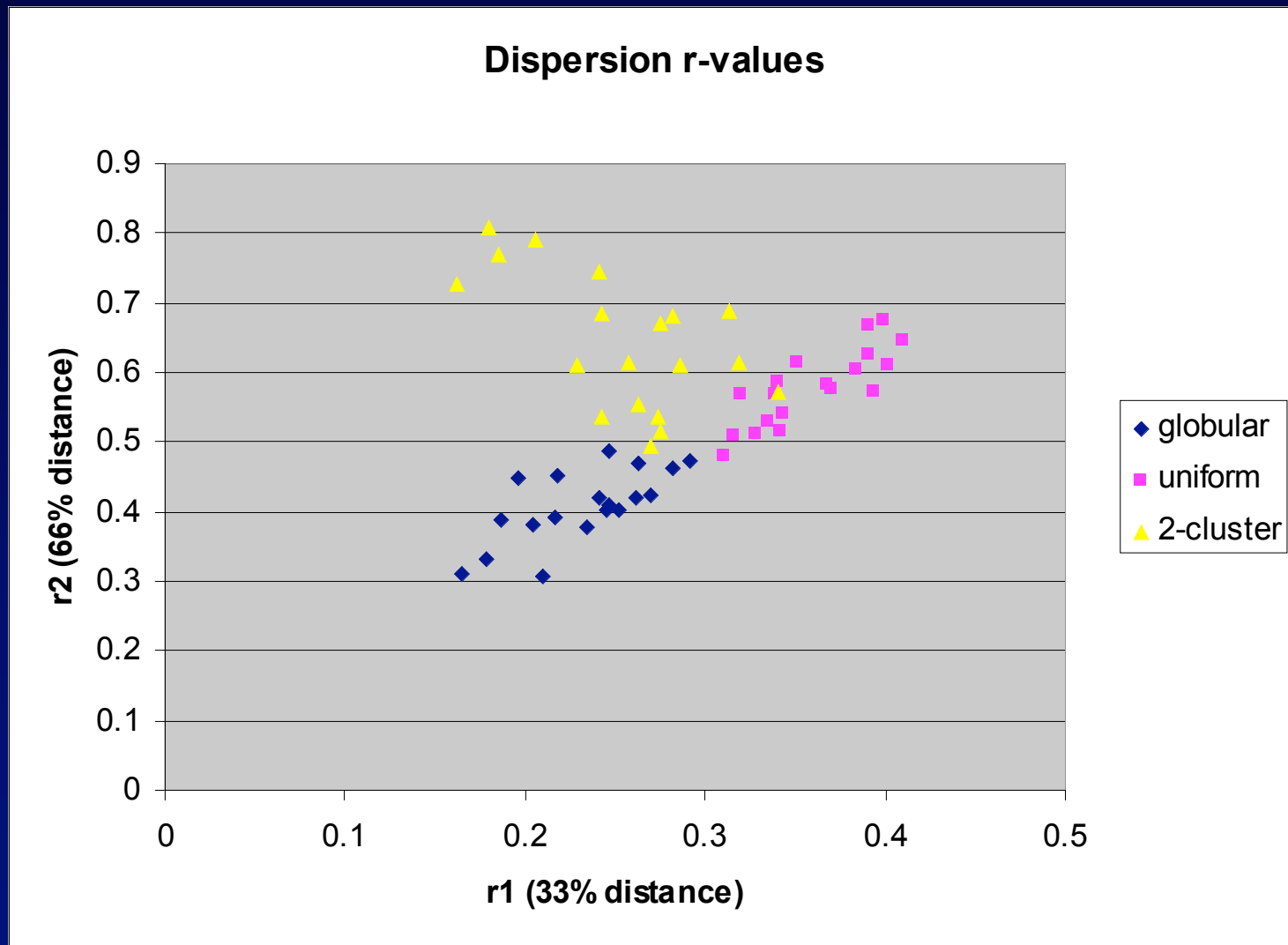


## Uniform

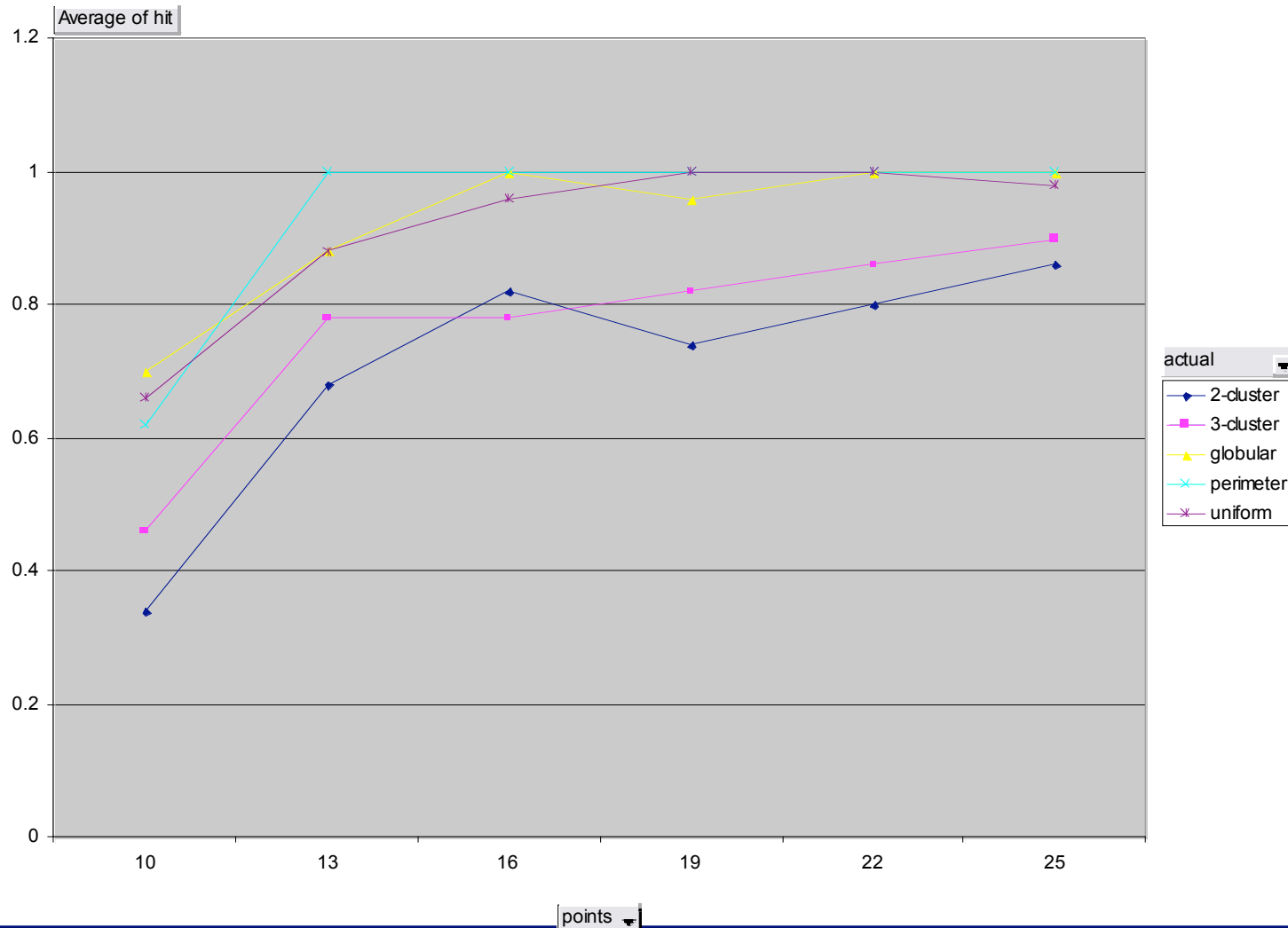


“Distograms” of sorted, normalized pair distances

# Classifying Dispersion Patterns



# Classifier Results



# Outline

- Apex: autonomy software overview
- Autonomous surveillance missions
- Automatically generating mission plans
- Observing targets
- Adapting to unplanned conditions
- Visualizing autonomy logic



# Observing Targets

## Goal

acquire *sensor data products* in support of surveillance task.

### Observation behavior elements

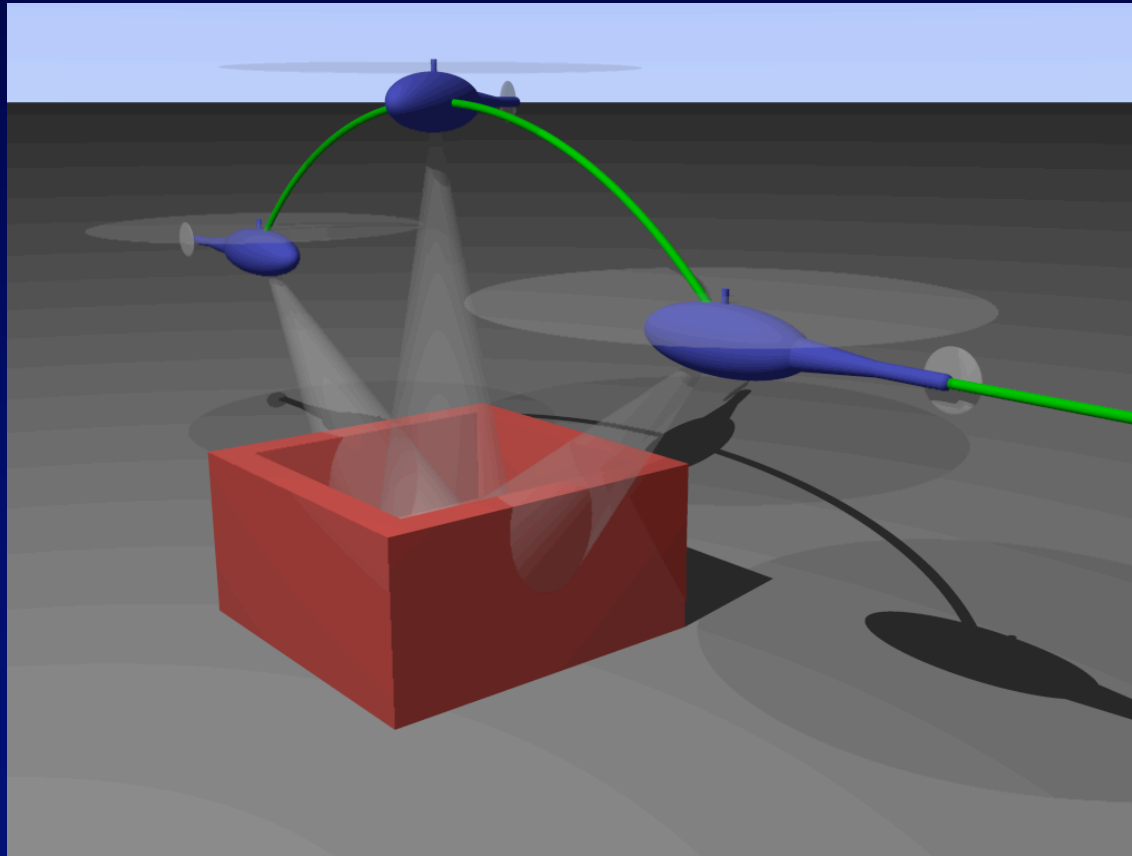
- Path
- Attitude mode changes
- Speed changes
- Sensor payload behavior (powerup, actuation, imaging)
- Data handling behavior (storage, compression, telemetry)

## Challenges

1. Large space of observing behaviors and need to link behavior to surveillance needs requires AI planning
2. Too much uncertainty for detailed advanced planning

# Observation Behaviors

## Arch with camera tracking



Compensating for limited camera actuation range

### Sequence

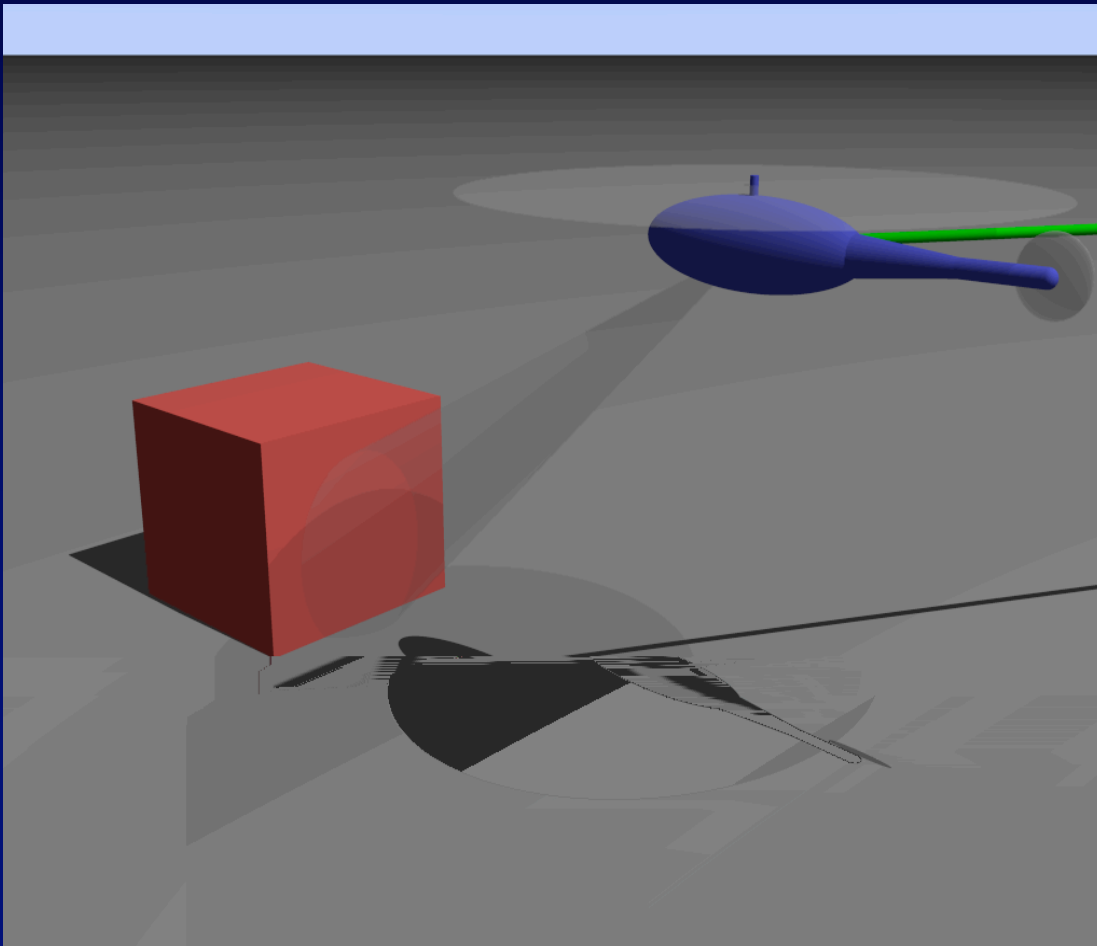
- move to standoff
- turn on video camera and track target
- climb to apex
- reduce speed
- reverse heading
- increase speed
- descend arch
- turn off camera

### Parameters

- View radius

# Observation Behaviors

## Pause and Stare (Best Vantage)



### View position factors

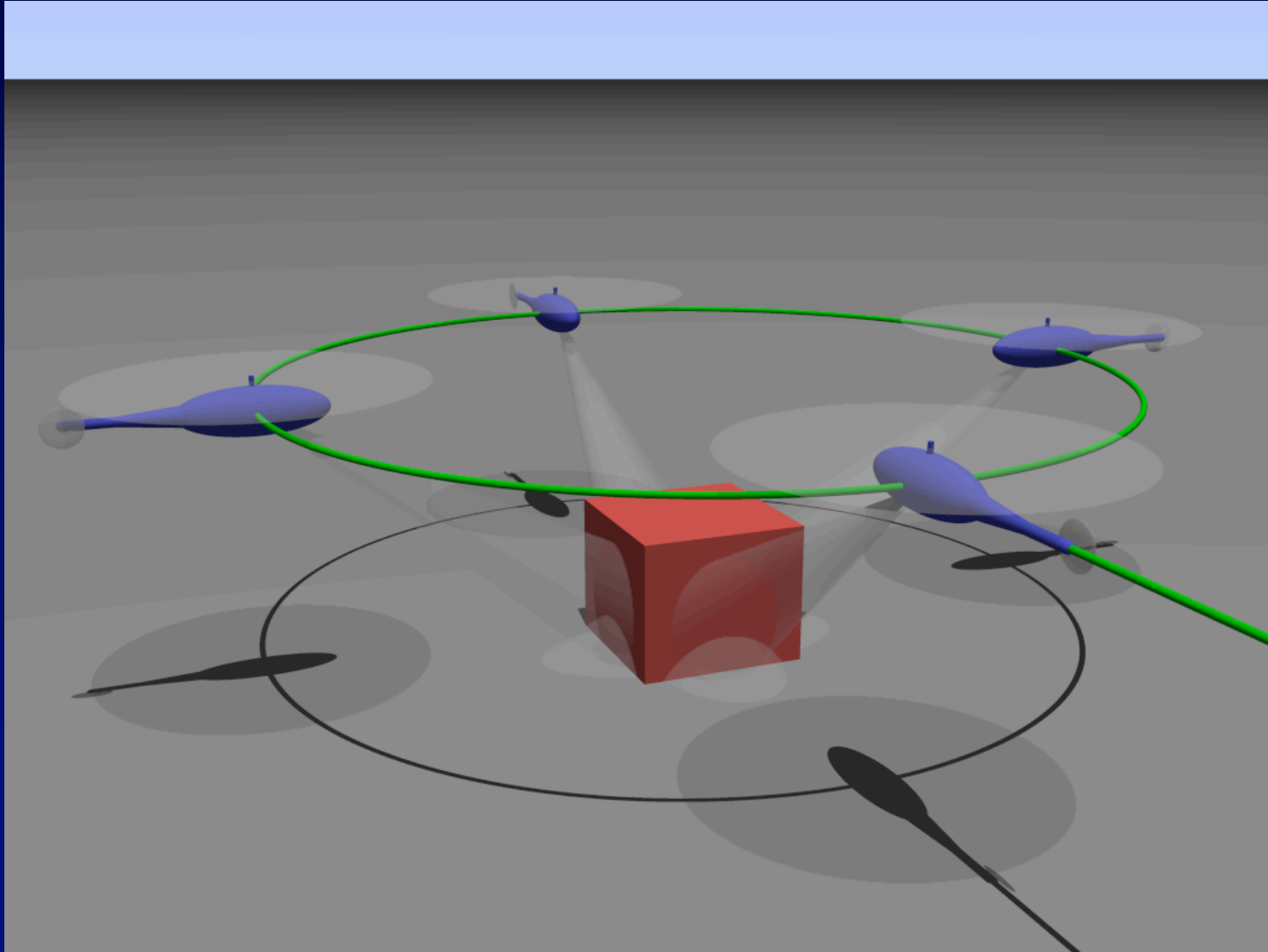
- Current sun position (shadows in image)
- Camera resolution
- Wind speed/direction
- Obstacles (line of sight)

### Parameters

- Pause duration
- Sensing action (image, video, laser sweep)

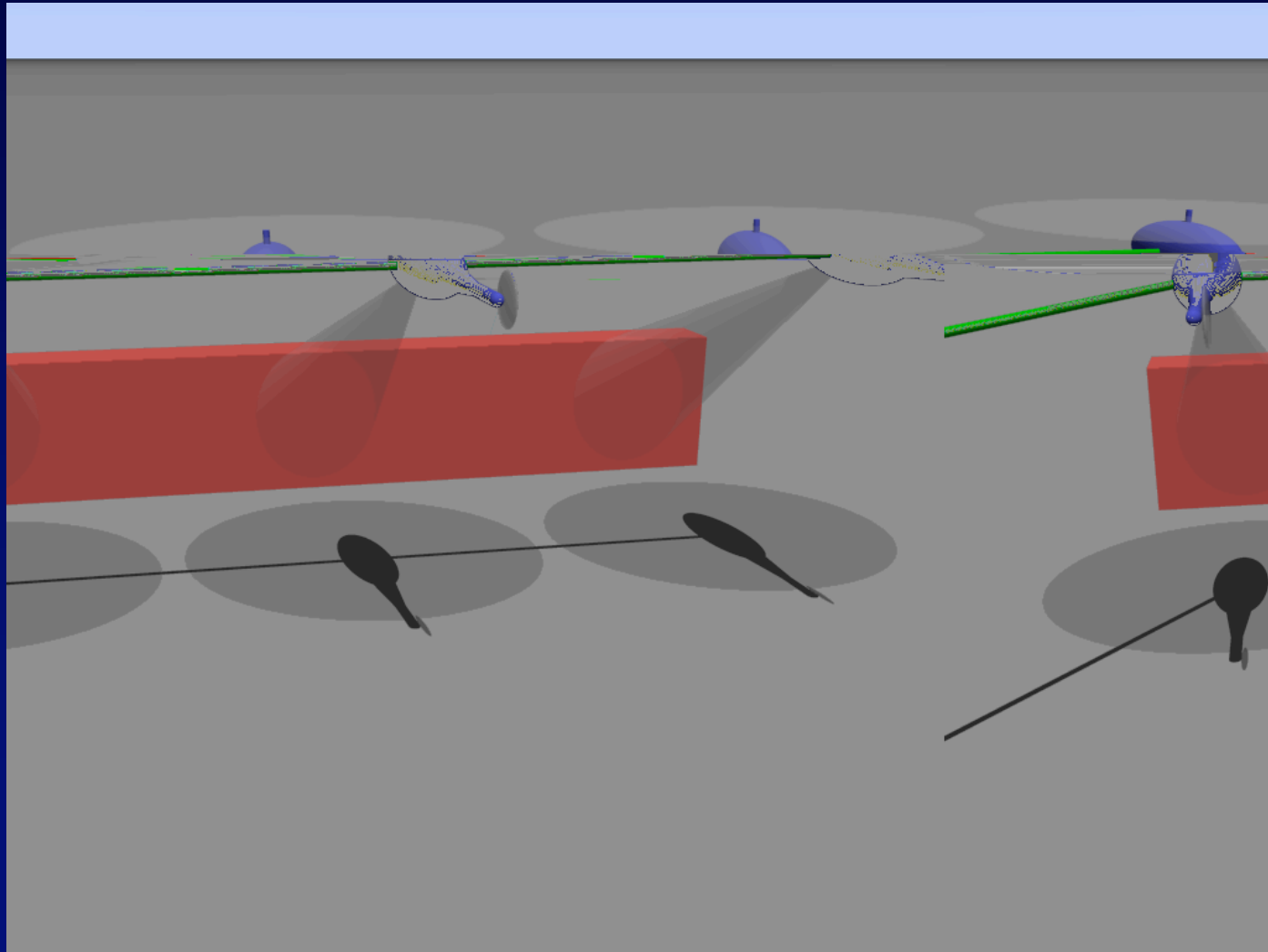
# Observation Behaviors

## Pirouette



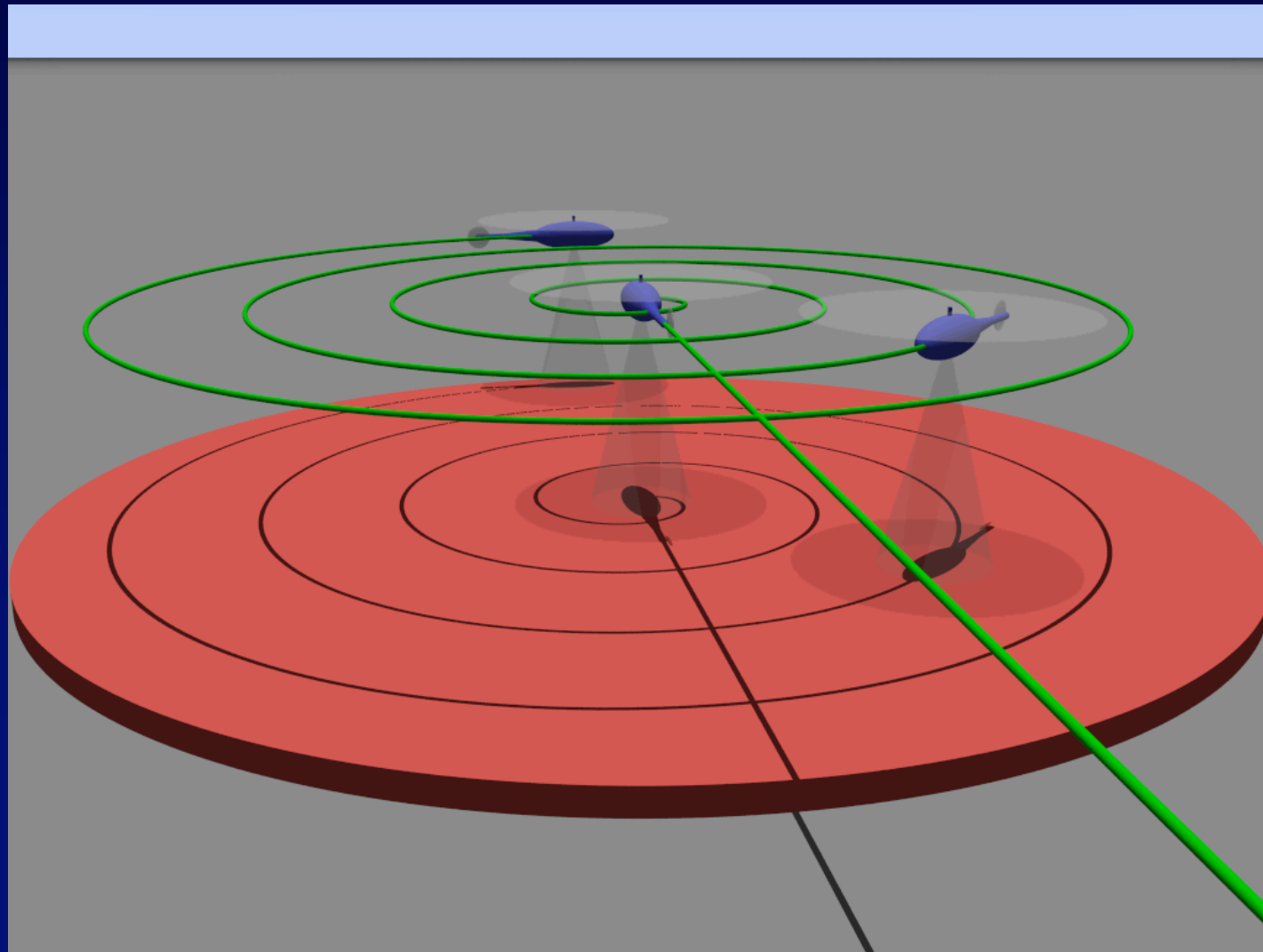
# Observation Behaviors

## Scan



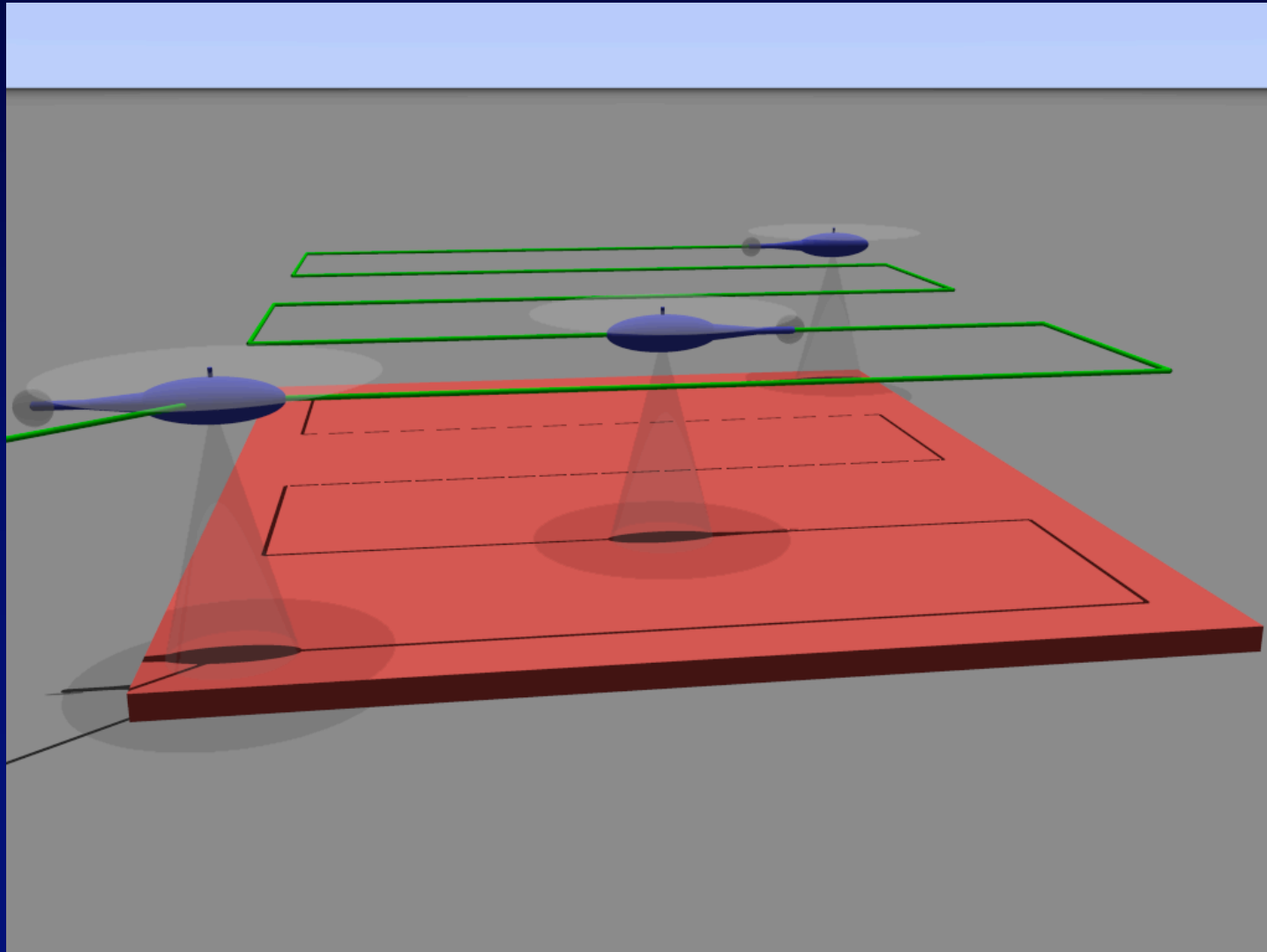
# Observation Behaviors

## Spiral



# Observation Behaviors

## Area Sweep



# Observation Behaviors

## Challenge

Observation behaviors can't always be planned out in detail in advance due to uncertainty about:

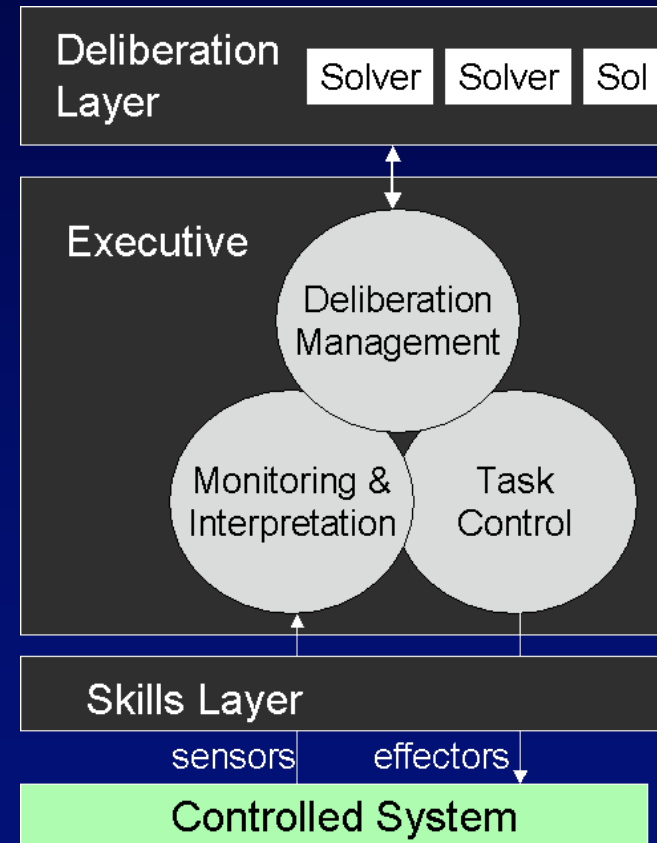
- Sun position (time of day)
- Wind
- View and path obstacles
- Most useful data product

It is useful to be able to leave the exact behavior unspecified in the mission plan until it is almost time to observe.



# Reasoning and Control Services

Dispatch  
Signal and process handling  
Condition detection  
Memory management  
**Refinement**  
Transformation  
Projection  
Self-calibration  
Deliberation control



# Outline

- Apex: autonomy software overview
- Autonomous surveillance missions
- Automatically generating mission plans
- Observing targets
- Adapting to unplanned conditions
- Visualizing autonomy logic

# Adaptation to unplanned conditions

*Planning is everything. Plans are nothing.* (D.D. Eisenhower)

**Problem:** almost any condition not precisely anticipated can invalidate a plan or reduce its effectiveness.

- **Operator interventions**

- Interval of manually controlled observation\*
- Change to mission goals or parameters\*

- **Unexpected outcomes**

- Quality of data product at target less than desired
- Unexpectedly long/short time to traverse; fuel consumed

- **System and operational environment contingencies**

- Loss of communication signal strength\*
- Loss of camera power
- Shift in wind

\* Illustrated in flight test

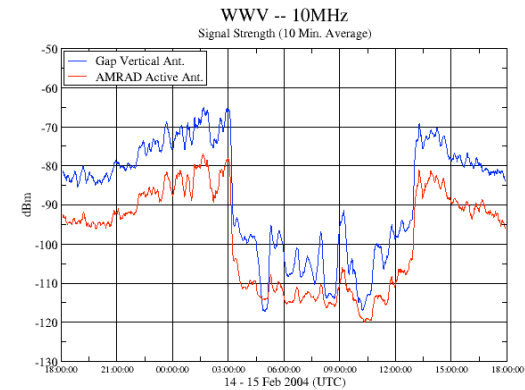
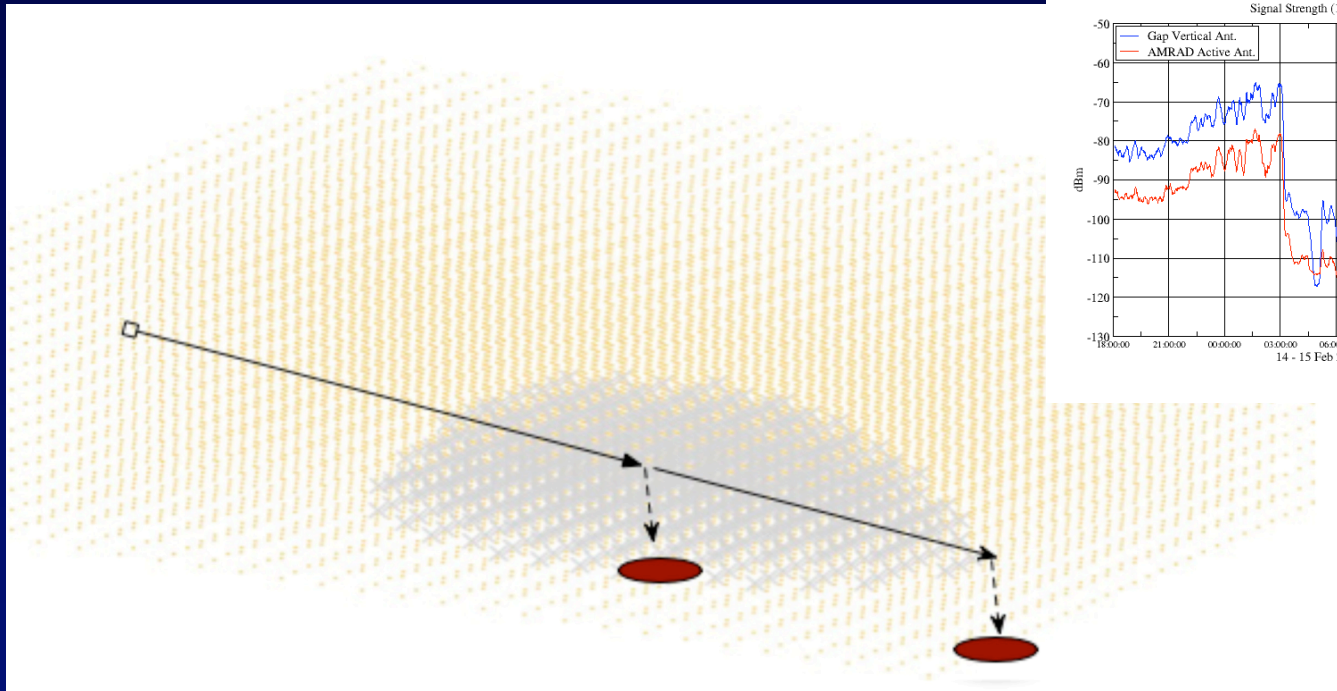
# Adaptation to unplanned conditions

## Handling anomalies

1. Detect the condition
2. Recover (if needed)
3. Determine modification to current plan to cope with the condition (if needed)
4. Assess impact of recovery/modification, then either:
  - Ignore anomaly and continue
  - Modify plan and continue
  - Throw out old plan and generate a new one

# Adaptation to unplanned conditions

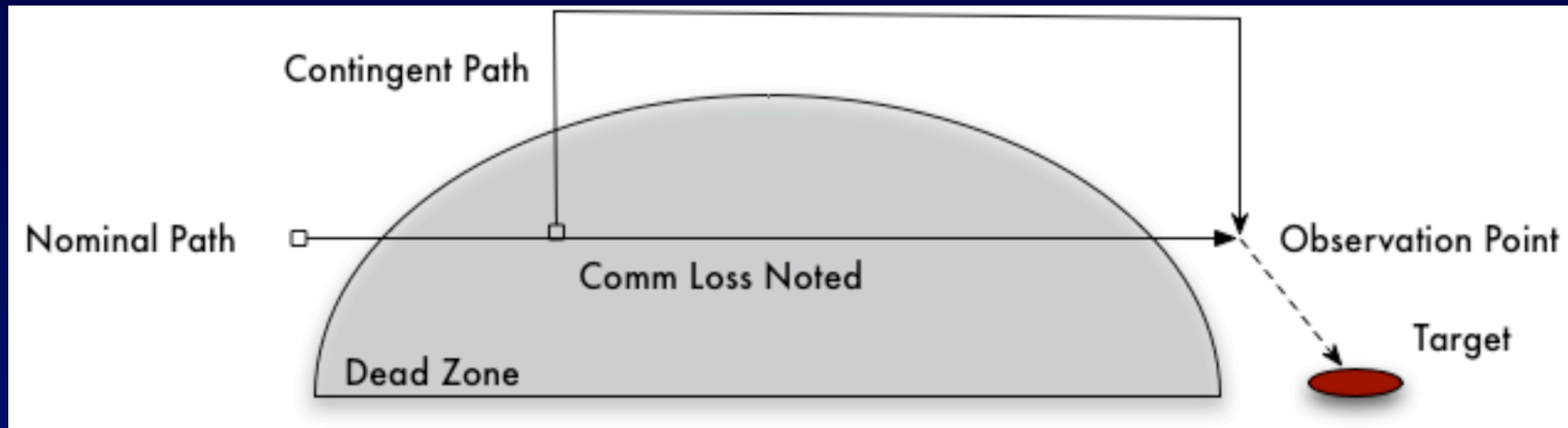
## Example: Loss of communication signal strength



Step 1: In transit to next target, loss of signal strength of sufficient magnitude and duration to trigger operational contingency occurs.

# Adaptation to unplanned conditions

Example: Loss of communication signal strength

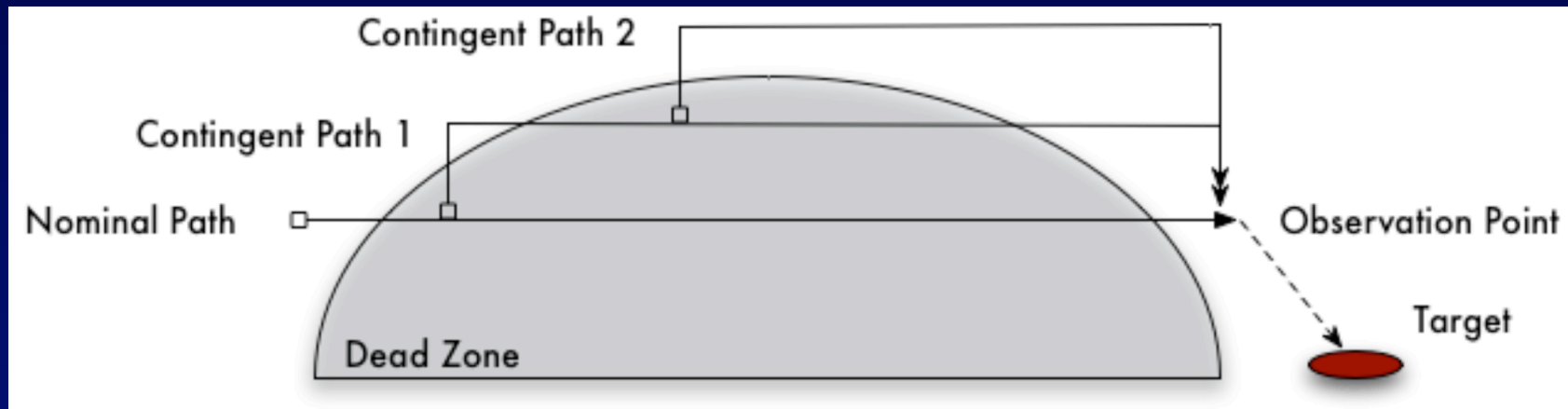


Step 2: Apex modifies plan: climb above comm loss area (and above preferred observation altitude); transit to next target; descend.

Step 3: Apex assesses impact of modification on mission plan. If time cost reduces number of targets reachable before mission end or violates plan constraint, then replan.

# Adaptation to unplanned conditions

Example: Loss of comm signal strength



If comm loss area extends higher than expected, additional climbing step(s) may be inserted into plan (requiring new replan assessment)

# Adaptation to unplanned conditions

## Reasoning and Control Services

### Dispatch

Signal and process handling

### Condition detection

Memory management

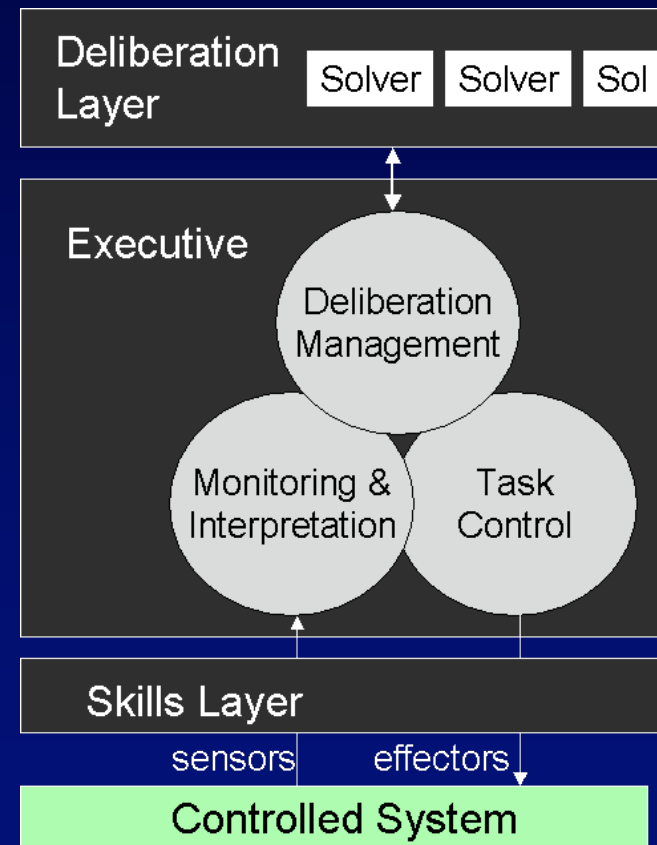
Refinement

### Transformation

### Projection

Self-calibration

Deliberation control





# Outline

- Apex: autonomy software overview
- Autonomous surveillance missions
- Automatically generating mission plans
- Observing targets
- Adapting to unplanned conditions
- Visualizing autonomy logic

# Apex Usability

Indirect contributions to the capabilities we've developed for ARP

- Behavior representation language (PDL)
- Debugging / critiquing (Sherpa)
- Application configuration
- User support

# Autonomy Visualization

- Visualizing behavior vs. visualizing logic
  - **Behavior**: what is happening, what did happen
  - **Logic**: what might happen or might have happened
    - Causal Explanation (complex behavior, incorrect behavior)
    - Predicting (planned, contingent futures)
- 4 points of view
  - Autonomy application developer
  - Systems engineer
  - Operator
  - Stakeholder

# Sherpa

## Integrated Debugging and Demonstration Environment

Browser interaction model for viewing data

8 ways to view autonomy logic

URL focal object All data objects as hypertext

forward/back buttons

Main Toolbar

Object Tree  
(Navigation)  
Window

Application  
Status Bar

The screenshot shows the Sherpa - X-Plane Demo (with takeoff error) application window. The interface includes a menu bar (File, View, Trace, Inspect, Window, Help), a main toolbar with buttons for Back, Forward, Reload, Reset, Run, Step, and Trace, and a set of icons for Diagram, Inspect, Agenda, and PDL. The Focal Object is set to 'realtime-application-1/locale-1/agent-1'. The Object Tree (Navigation) Window on the left displays a hierarchical structure of the application, including X-PLANE-WORLD, XP-PILOT, Resources, Agenda, and Procedures. The Main View Window on the right displays a table of events with columns for Timestamp, Agent, Event Type, Task ID, and Description. The Application Status Bar at the bottom shows the state as PAUSED and the time as 9767.

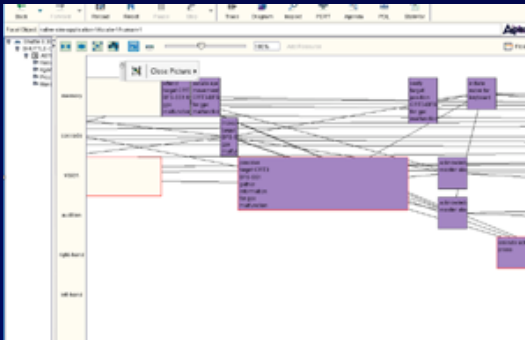
Timestamp	Agent	Event Type	Task ID	Description
4221	xp-pilot	task-started	2	(fly traffic pattern)
4463	xp-pilot	task-started	3	(setup selecting plane Altair)
4560	xp-pilot	task-started	9	(select-aircraft Altair)
4580	xp-pilot	task-started	10	(select-runway KSD 06x)
4695	xp-pilot	task-started	4	(takeoff)
4733	xp-pilot	task-started	12	(setup for takeoff)
4814	xp-pilot	task-started	13	(extend flaps for takeoff)
4840	xp-pilot	task-started	15	(release brakes at 70 percent of power)
4856	xp-pilot	task-started	34	(ask (AIRCRAFT-TYPE B-ER Altair) for horse-power)
4869	xp-pilot	task-started	35	(ask (AIRCRAFT-TYPE B-ER Altair) for engine-count)
4959	xp-pilot	task-started	31	(ask (AIRCRAFT-TYPE B-ER Altair) for flaps-takeoff)
5041	xp-pilot	task-started	32	(set-flaps 0.6667)
5124	xp-pilot	task-started	21	(autopilot-disable-all)
5452	xp-pilot	task-started	22	(compute-runway-heading-magnetic)
5457	xp-pilot	task-started	25	(autopilot-hold vertical 0.0)
5727	xp-pilot	task-started	26	(xplane-enable-measurements (flap-postn power1-hp power2-hp vind-kias alt-flap
5925	xp-pilot	task-started	38	(ask (RUNWAY: KSD 06x) for heading-true)
5955	xp-pilot	task-started	39	(xplane-query-value mavar-deg)
5964	xp-pilot	task-started	27	(ask (AIRCRAFT-TYPE B-ER Altair) for ias-rotate)
5971	xp-pilot	task-started	42	(xplane-enable-measurement mavar-deg)
5987	xp-pilot	task-started	28	(ask (AIRCRAFT-TYPE B-ER Altair) for agl-gear-up)
5995	xp-pilot	task-started	28	(ask (AIRCRAFT-TYPE B-ER Altair) for agl-gear-up)
6004	xp-pilot	task-started	29	(xplane-query-value vfe-ktas)
6011	xp-pilot	task-started	45	(xplane-enable-measurement vfe-ktas)
6040	xp-pilot	task-started	24	(xplane-set-rudder-yoke 0.0)
6253	xp-pilot	task-started	43	(xplane-disable-measurement mavar-deg)
6300	xp-pilot	task-started	40	(compute-delta-heading 70.36 -13.615474)
6340	xp-pilot	task-started	23	(autopilot-hold heading 56.744514)
6944	xp-pilot	task-started	46	(xplane-disable-measurement vfe-ktas)
7201	xp-pilot	task-started	14	(set throttle to 100 percent)
7205	xp-pilot	task-started	17	(raise gear)

Inspect  
Trace  
Diagram  
PERT (schedule)  
Agenda (tree)  
PDL (template)  
Monitor  
State Variable

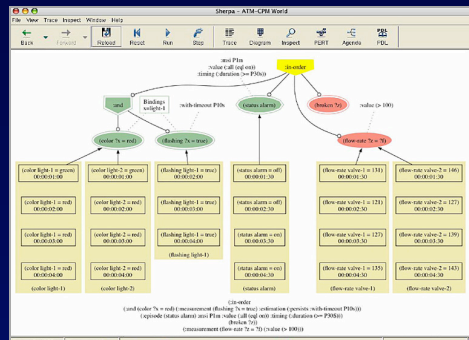
Main View  
Window

Communication  
Status Indicator

# Sherpa views



## PERT chart



## Event Monitoring Logic / History


Task	Task ID	Sub-task	Start	Task	Progress	Time in Status
(x) (downward)	Task-0	terminated	engaging			77497
(x) (downward and to right)	Task-3	terminated	engaging			64139
(x) (near forward health targets)	Task-4	terminated	engaging			63778
(x) (monitor targets)	Task-5	terminated	engaging			63745
(x) (near forward)	Task-7	terminated	engaging			63745
(x) (near mission "transformation mission accepted")	Task-8	terminated	engaging			63727
(x) (by the side)	Task-9	terminated	engaging			63549
(x) (near miss escape range "ready for targets...")	Task-10	terminated	engaging			49172
(x) (carry vehicle status)	Task-20	terminated	engaging			38837
(x) (by mission type mission)	Task-21	terminated	engaging	(person)		39039
(x) (survive targets)	Task-28	terminated	engaging			39395
(x) (survive targets)	Task-30	terminated	engaging			39339
(x) (survive targets)	Task-32	terminated	engaging			39339
(x) (survive targets)	Task-38	terminated	engaging			39339
(x) (survive targets)	Task-39	terminated	engaging			39339
(x) (survive targets)	Task-40	terminated	engaging			39339
(x) (by target target)	Task-41	terminated	engaging	(person)		39339
(x) (by target target)	Task-42	terminated	engaging			39339
(x) (near mission "operations forward")	Task-43	terminated	engaging			39339
(x) (near mission "operations forward")	Task-44	terminated	engaging			39339
(x) (near mission "operations forward")	Task-45	terminated	engaging			39339
(x) (near mission "operations forward")	Task-46	terminated	engaging			39339
(x) (near mission "operations forward")	Task-47	terminated	engaging			39339
(x) (near mission "operations forward")	Task-48	terminated	engaging			39339
(x) (near mission "operations forward")	Task-49	terminated	engaging			39339
(x) (near mission "operations forward")	Task-50	terminated	engaging			39339
(x) (near mission "operations forward")	Task-51	terminated	engaging			39339
(x) (near mission "operations forward")	Task-52	terminated	engaging			39339
(x) (near mission "operations forward")	Task-53	terminated	engaging			39339
(x) (near mission "operations forward")	Task-54	terminated	engaging			39339
(x) (near mission "operations forward")	Task-55	terminated	engaging			39339
(x) (near mission "operations forward")	Task-56	terminated	engaging			39339
(x) (near mission "operations forward")	Task-57	terminated	engaging			39339
(x) (near mission "operations forward")	Task-58	terminated	engaging			39339
(x) (near mission "operations forward")	Task-59	terminated	engaging			39339
(x) (near mission "operations forward")	Task-60	terminated	engaging			39339
(x) (near mission "operations forward")	Task-61	terminated	engaging			39339
(x) (near mission "operations forward")	Task-62	terminated	engaging			39339
(x) (near mission "operations forward")	Task-63	terminated	engaging			39339
(x) (near mission "operations forward")	Task-64	terminated	engaging			39339
(x) (near mission "operations forward")	Task-65	terminated	engaging			39339
(x) (near mission "operations forward")	Task-66	terminated	engaging			39339
(x) (near mission "operations forward")	Task-67	terminated	engaging			39339
(x) (near mission "operations forward")	Task-68	terminated	engaging			39339
(x) (near mission "operations forward")	Task-69	terminated	engaging			39339
(x) (near mission "operations forward")	Task-70	terminated	engaging			39339
(x) (near mission "operations forward")	Task-71	terminated	engaging			39339
(x) (near mission "operations forward")	Task-72	terminated	engaging			39339
(x) (near mission "operations forward")	Task-73	terminated	engaging			39339
(x) (near mission "operations forward")	Task-74	terminated	engaging			39339
(x) (near mission "operations forward")	Task-75	terminated	engaging			39339
(x) (near mission "operations forward")	Task-76	terminated	engaging			39339
(x) (near mission "operations forward")	Task-77	terminated	engaging			39339
(x) (near mission "operations forward")	Task-78	terminated	engaging			39339
(x) (near mission "operations forward")	Task-79	terminated	engaging			39339
(x) (near mission "operations forward")	Task-80	terminated	engaging			39339
(x) (near mission "operations forward")	Task-81	terminated	engaging			39339
(x) (near mission "operations forward")	Task-82	terminated	engaging			39339
(x) (near mission "operations forward")	Task-83	terminated	engaging			39339
(x) (near mission "operations forward")	Task-84	terminated	engaging			39339
(x) (near mission "operations forward")	Task-85	terminated	engaging			39339
(x) (near mission "operations forward")	Task-86	terminated	engaging			39339
(x) (near mission "operations forward")	Task-87	terminated	engaging			39339
(x) (near mission "operations forward")	Task-88	terminated	engaging			39339
(x) (near mission "operations forward")	Task-89	terminated	engaging			39339
(x) (near mission "operations forward")	Task-90	terminated	engaging			39339
(x) (near mission "operations forward")	Task-91	terminated	engaging			39339
(x) (near mission "operations forward")	Task-92	terminated	engaging			39339
(x) (near mission "operations forward")	Task-93	terminated	engaging			39339
(x) (near mission "operations forward")	Task-94	terminated	engaging			39339
(x) (near mission "operations forward")	Task-95	terminated	engaging			39339
(x) (near mission "operations forward")	Task-96	terminated	engaging			39339
(x) (near mission "operations forward")	Task-97	terminated	engaging			39339
(x) (near mission "operations forward")	Task-98	terminated	engaging			39339
(x) (near mission "operations forward")	Task-99	terminated	engaging			39339

# Task Agenda

Task Manager Performance tab - Processes section

Process Name	CPU	Private Bytes	Working Set	Private Bytes	Working Set
System	0%	1,048,576 KB	1,048,576 KB	1,048,576 KB	1,048,576 KB
smss.exe	100%	1,048,576 KB	1,048,576 KB	1,048,576 KB	1,048,576 KB

# Event Trace



Visual Studio Code editor showing the 'index.html' file. The code is as follows:

```

<!DOCTYPE html>
<html>
  <head>
    <title>index.html</title>
    <meta charset="utf-8">
    <link href="css/index.css" rel="stylesheet">
  </head>
  <body>
    <h1>index.html</h1>
    <p>index.html</p>
    <form>
      <input type="text">
      <input type="submit" value="Submit">
    </form>
  </body>
</html>

```

## Behavior Specifications

# Conclusion

- Apex provides capability for full mission autonomy in complex missions
- Surveillance planning is something best done by autonomous systems
- Executing plans would be easy if the world were predictable, but it's not.
- Reusability is important: building capable, reliable, usable autonomy software is too difficult to do repeatedly for every new platforms and missions.

# For more information

Web site <http://ti.arc.nasa.gov/projects/apex/>

- ARP project description, online MPI demo
- Publications
- Download software (open source)

Email: Michael.A.Freed@nasa.gov

# Apex Outer-Loop Control Block Diagram

